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NOVA LASER SYSTEM FOR INERTIAL CONFINEMENT FUSION*

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Summary

The Nova laser fusion research facility, currently under construction at LLNL, and authorized by Congress at $195M, will provide researchers with powerful new tools for the study of nuclear weapons physics and inertial confinement fusion. Nova is a large, solid state laser, generating a fundamental wavelength of 1.0 μm, intended to deliver 200-300 kJ in a few nanoseconds to appropriate advanced inertially confined fusion targets containing deuterium and tritium. At these drive levels, we are confident that conditions of thermonuclear ignition can be reached; furthermore, when frequency conversion to shorter wavelengths (.5 μm and .35 μm) is implemented, there is a chance for scientific breakeven (kinetic energy of the reaction particles exceeding incident laser energy on target). The Department of Energy (DOE) has approved construction of ten Nova laser beams and the associated laboratory buildings. The remaining ten beams, and harmonic conversion apparatus, is presently under consideration.

The Nova laser consists of 20 large (74-cm diam) beams, focused, synchronized and aligned precisely so that their combined energy is brought to bear for a small fraction of a second on a single target. The ultimate goal of the LLNL inertial confinement fusion program is to produce fusion microexplosions that release several hundred times the energy that the laser delivers to the target. Such an achievement would make inertial confinement fusion attractive for both military and civilian applications. By the mid- to late 1980s, Nova should demonstrate that we can produce the extremes of heat and pressure required to achieve ignition of the thermonuclear fuel. Additional developments in the area of high-efficiency drivers and reactor systems may make inertial confinement fusion attractive for commercial power production.

Introduction

Over the past several years, LLNL has built and operated a series of increasingly powerful and energetic laser systems to study the physics of inertial confinement fusion (ICF) targets and laser-plasma interactions. Nova, the latest in this series, is the successor to the Argus and Shiva lasers. The Nova laser will consist of 20 beams, capable of concentrating 200 to 300 kJ of energy (in 3 ns) and 200 to 300 TW of power (in 100 ps) on experimental targets by the mid- 1980s. It will be housed partly within the existing Shiva building and partly within a new 10684-m^2 (115,000 ft^2) laboratory building adjacent to the existing Shiva facility (see Fig. 1).

Laser Design and Performance

The Nova laser system has master-oscillator-power-amplifier (MOPA) architecture. As shown in Fig. 2, a laser pulse of requisite temporal shape is generated by the oscillator, preamplified, and split

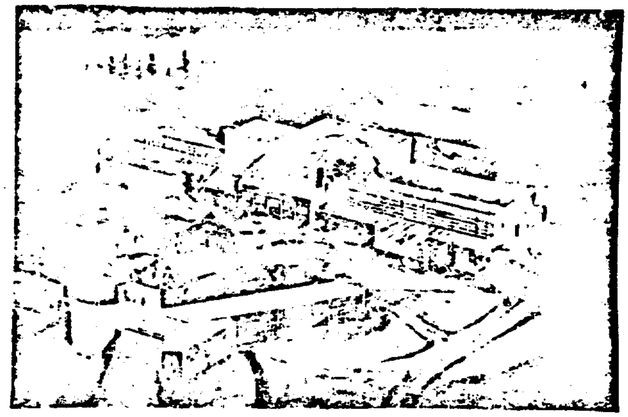

Fig. 1 - Artist's conception of the Nova laser fusion facility in a cutaway aerial view.

into 20 beams. After traversing an adjustable optical delay path (used to synchronize the arrival of the various beams at the target), the pulse enters the amplifier chain, where (1) disk amplifiers increase the pulse power and energy, (2) spatial filters maintain the spatial smoothness of the beam profile while expanding its diameter, and (3) isolators prevent the entire laser from breaking spontaneously into oscillations that could drain its stored energy and damage the target prematurely.

The beam is collimated between spatial filters in the laser chain. Thus, each of the components in a particular section has the same diameter. In the 4.0 cm section (see Fig. 2), the amplifier is a single glass rod, and the isolator is an electro-optic (Pockels) cell crystal placed between crossed polarizers. This cell operates as a fast (10 ns) optical gate, preventing interchain oscillations and at the same time reducing to tolerable levels unwanted amplified spontaneous emission (i.e., radiation at the laser wavelength, amplified by passage through the chain, which can strike and damage the target before the laser pulse arrives). In all larger diameter sections, the amplifiers consist of face-pumped disks set at Brewster's angle to the passing beam. Polarization-rotating isolators, relying upon the Faraday effect, assure interchain isolation.

Optimum spatial filter design provides entrance-lens-to entrance-lens imaging. Thus, smooth beam intensity (through the cross-sectional area) is projected along the chain, and energy extraction by the laser pulse is maximized. Nearly all solid state laser systems now incorporate this multiple sequential spatial filter design approach.

When the pulse exits from the final beam-expanding spatial filter, it has been amplified to an energy level of 10 to 15 kJ, and its diameter is 74 cm. Turning mirrors direct the beam to the target

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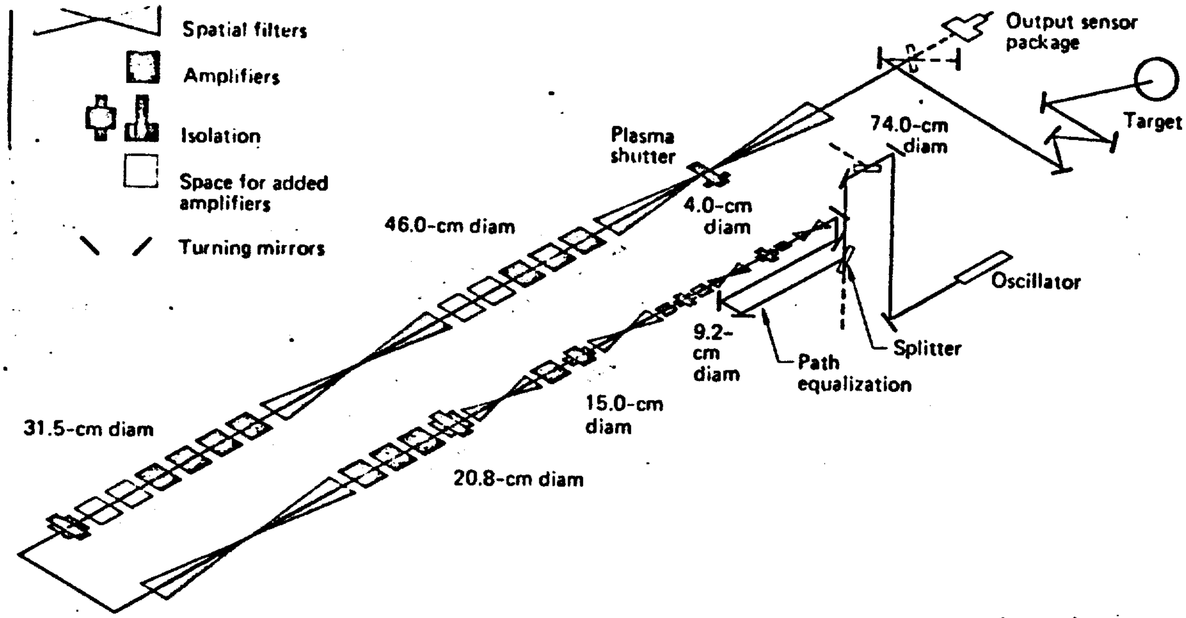

Fig. 2 - Schematic diagram illustrating the major optical components through which each (of 20) Nova laser beams will pass on its way from the oscillator (optical pulse generator) to the target.

chamber, where focusing lenses concentrate it on the target. The first of the turning mirrors is partially transparent, allowing approximately 2% of the pulse to enter the output sensor package. This unit senses and reports on the alignment status, energy and power, spatial quality, and other characteristics of the beam. The plasma shutter, located at the focal position of the final spatial filter, protects the laser by preventing light reflected from the target from reaching the laser amplifiers. In the absence of this protection, such light would travel back down the chain (being amplified in the process), and it might damage or destroy some of the optical components.

In each section, the beam is amplified to the damage threshold of the lenses at a maximum energy output for a specified pulse duration. This "isofluence" design maximizes the energy output per unit cost, while keeping the chain as a whole below the component damage limit. The fluence (energy per unit area) at which optical components suffer damage exhibits a temporal dependence, as shown in Table I.

Table I

	Damage threshold, J/cm2		
	0.1 ns	1.0 ns	3.0 ns
Coated surfaces	2.5	8.0	8.5
Bare polished surfaces	6.0	19	33

It is apparent that uncoated surfaces will tolerate higher fluences than antireflection coated (AR-coated) surfaces. Thus, spatial filter input lenses, which are subject to the highest peak fluences, are left uncoated as the pulse passes through the various amplifier sections. The average fluence grows as a result of amplification of the pulse energy. However, the peak fluence grows faster because it is affected by both nonlinear self-focusing and diffraction from spatial noise sources. Beam expanding spatial filters reduce both the average fluence and the peak/average intensity ratio. Thus, the spatial filter output lenses and the target lens can be AR-coated.

Output power and energy performance for one Nova beam is summarized in Fig. 3. The upper curve represents hypothetical single-chain performance at the first-component-to damage limit if a perfectly smooth beam with a 70% filling factor were to pass through it. However, real beams exhibit spatial modulation as a result of imperfections encountered upon passage through optical components. Therefore, realistic performance levels must be set on the basis of the peak/average ratio of the beam at the location of the threatened component. Computer estimates and operating experience with Shiva and Argus lasers lead to the lower curve, which represents an upper limit on performance of the laser at any pulse duration.

The full Nova complement of 20 beams will be brought to an integrated target chamber in two opposed clusters of 10 beams each.

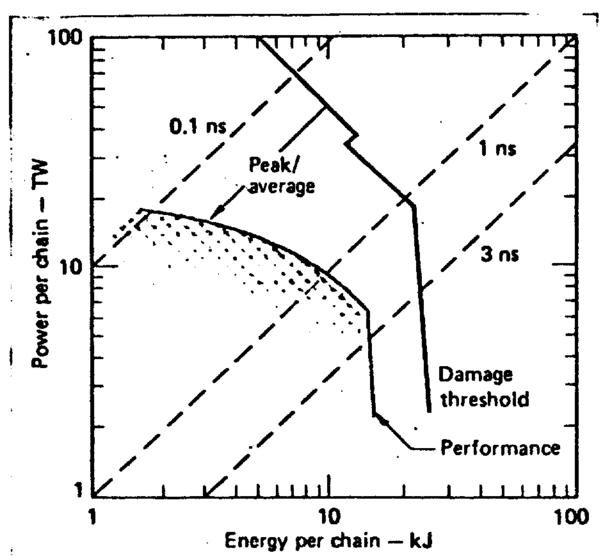

Fig. 3 - Performance limits, set by the threshold for beam damage to optical components, over the full temporal design range of Nova (0.1 to 3 ns). The operational regime is indicated by shading.

Figure 4 is an artist's conception of the Nova target chamber. The west beams are equally spaced in angle upon the surface of a 100° cone whose vertex is at the target. These beams are opposed by the east beams so that east and west beams can radiate

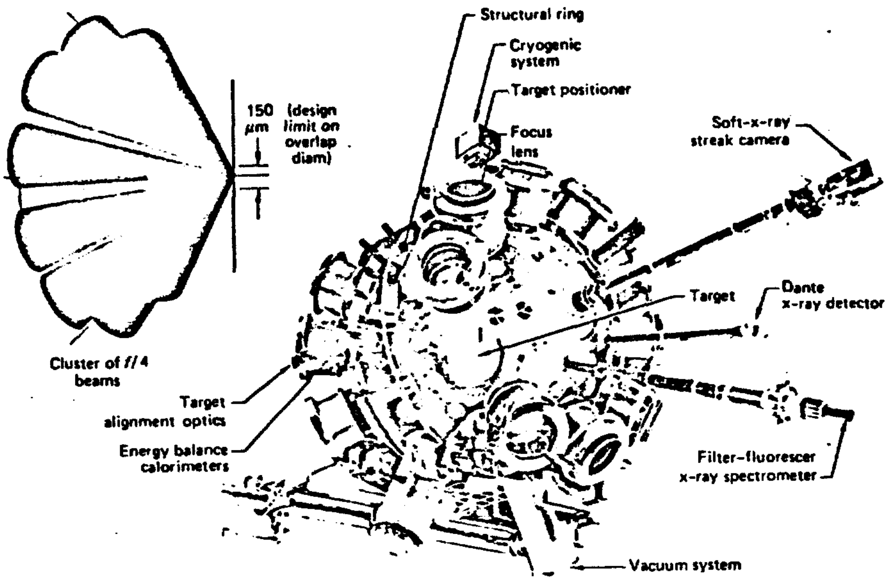

Fig. 4 - Artist's conception of the Nova target chamber, showing typical positions of some of the major experimental diagnostics. As shown in the insert (left), the beams in each of two opposed clusters are positioned on the surface of a 100° cone centered at the nominal target position.

into each other through a coordinate system centered at the target. Some of the ancillary target event diagnostics systems are also shown.

The line drawing in Fig. 4 illustrates design criteria for the overlap of Nova beams at a representative target. In the (common) focal plane, the beam overlap spot is not to exceed 150 μm in diameter, including allowances for alignment, positioning, and verification tolerances. This criterion applies for a nominal focal length of 3.0 m.

Key Components

Disk amplifiers and other components with apertures of 21 cm or less are typical of Shiva based technology. The larger Nova amplifiers will feature a new rectangular internal geometry (as opposed to the current cylindrical geometry) that will permit flashlamps to pump the laser disks more efficiently. A side view of a partially assembled 46 cm rectangular amplifier is shown in Figure 5.

Flashlamps run along two opposing sides of the rectangular case. Each flashlamp is backed by a silver-plated, crenulated reflector, which reflects light into the disk faces while minimizing absorption by neighboring flashlamps. Flat, silver-plated walls form the remaining two sides. The cavity is very reflective and provides tight optical coupling of light from flashlamps to disks. Careful design has produced significant efficiency improvements over prior amplifiers. We will employ rectangular disk amplifiers in the final three amplifier sections of Nova. Design criteria, most of which have been met in component tests, are summarized in Table 2.

Phosphate-based glass features very high intrinsic gain, as well as sufficient energy storage capacity for the realization of Nova laser performance goals. Furthermore, it has proven to be manufacturable in large sizes to Nova specifications relating to optical quality and resistance to damage. We have, therefore, chosen phosphate to be the host material for the active Neodymium ions.

Table II

	Amplifier aperture, cm		
	20.8	31.5	46
Glass type	Phosphate	Phosphate	Phosphate
Number of lamps/amplifier head	16	20	80 (transverse)
Number of disks/amplifier head	3	2	2 (split)
Stored energy (nominal), kJ	300	375	600
Small signal gain/head (nominal)	2.3	1.78	1.98

With disks of large diameter, the gain path for internally generated amplification of spontaneous emission (ASE) becomes longer. Internal ASE represents a parastic drain on the energy stored in each disk. At the largest Nova amplifier diameter (46 cm), drastic measures must be taken to suppress this drain. This is the reason why the disks are split along their minor diameters. Much higher energy storage and gain can be realized from a 46 cm diameter disk when it is split as shown in Fig. 5.

In order to protect the laser itself from light returning from the target, an absorbing plasma is injected into the final spatial filter near the location of its common focus. This plasma "shutter" consists of a wire (or foil) metallic sample closing an electric circuit. This circuit stands ready until the optical pulse has passed the pinhole at the final spatial filter. At that instant, an electrical surge large enough to sublimate the foil is applied. This creates a plasma jet, which is directed transverse to the beam path near the pinhole. The driving current pulse must be very rapid to create the plasma, which blocks light reflected from the target. (Such light reappears at the plasma within about 400 ns). Consequently, advanced rail-gap technology has been used to minimize electrical circuit inductance. Tests have confirmed that the 3 cm/μs plasma velocity that is created with an energy store of 6 kJ is sufficient to ensure closure. Instrumentation within the device senses malfunctions (for example, prefire) and, through the power controls system, prevents the laser pulse from arriving at this point, thus "aborting" the shot.

Further details of the laser components, in terms of their design criteria, design performance, and fabrication will be presented in several of the following papers.

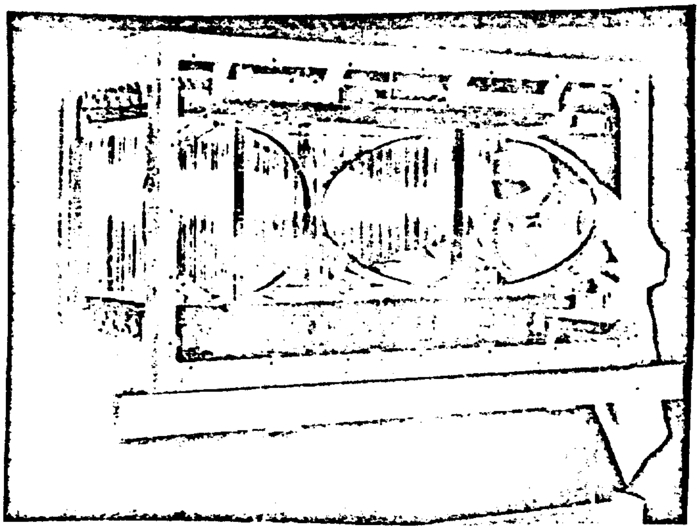

Fig. 5 - Partially assembled view of the 46-cm aperture rectangular laser disk amplifier. Half-disks are inserted in their elliptical holders. Transverse flashlamps and their reflectors appear at the rear of the amplifier. Interior metal parts are insulated to 50 kV to prevent arc-over. Most of the metal parts are electroformed nickel; Optical cavity interior parts are silver plated for high reflectivity.

Subsystems

The capacitive energy store for Nova active components (flashlamps and Faraday rotators) exceeds 120 MJ. It is extensively instrumented to provide real time circuit component fault detection (there are more than 2800 flashlamp circuits). Information concerning the state of the electrical components, as well as charge and fire command controls, is transmitted between energy storage areas and central controls over an extended bus system based upon fiber optics circuits. Additional features of the power conditioning subsystem will be described in a later paper in this session.

Complex systems like Nova, requiring literally thousands of electronic and electromechanical control functions for a single laser target experiment, must rely upon an extensive, sophisticated computer-control network. The control system architecture is designed to handle multiple tasks (such as laser alignment, target alignment, capacitor-bank charge and fire sequencing, and laser and target diagnostic data processing) from a centralized location. Common hardware and software routines allow functional redundancy. For example, two (of the three) VAX-11/780 computers are capable of operating the entire system through a task-sharing network. The same is true of the operator touch-panel display consoles, which are interchangeable.

The control system communicates with many distributed devices through an extensive fiber optic network, featuring high data transfer rates (10 Mbit/s), low overhead through direct access to computer memory, and programmable network connections. To facilitate block data transfer, which is especially useful for image data processing, the sophisticated Novanet interconnection system has been implemented using intelligent "Novalink" controllers, which can communicate both to remote LSI-11/23 computers and to remote memories of stored video images through fiber optics communication channels. Extensive discussions of various aspects of the control system will be presented in several of the papers to follow.

The alignment/diagnostics subsystem ensures that the laser pulse will: (a) pass through all of the laser components without vignetting; (b) arrive at target at the proper time, with the proper energy/power characteristics, and in the multibeam geometrical configuration prescribed by the experiment; and (c) verify that these events have occurred during the post-shot analysis. Alignment of the laser system is planned to be automated, and achievable (from "warm" start) within 30 minutes. The subsystem relies heavily upon communications via Novanet with central controls, and features extensive deployment of image-processing CCD array cameras. This subsystem will be elaborated upon in a paper during this session.

Frequency Conversion

Target experiments with wavelengths shorter than 1.0 μm have validated significant improvements in light-plasma coupling physics. Experiments with smaller lasers have demonstrated the feasibility of frequency conversion, with Nova, to target irradiation light of wavelengths 0.525 μm and/or 0.35 μm, with little loss of focusable energy or power. Accordingly, we are proposing that Nova incorporate this capability within its mission guidelines. Frequency conversion can be accomplished by the deployment of arrays of potassium dihydrogen phosphate (KDP) crystals between the laser and the target. The concept is shown in Figure 6, and discussed in some detail in a later article in this session.

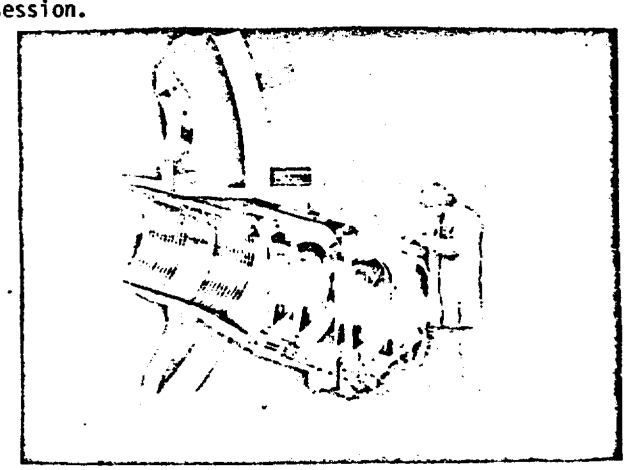

Fig. 6 - Artist's conception of the component arrangement comprising the frequency conversion array and doublet target focusing lenses. Beam aperture is 74 cm; doublet effective focal length is 3 meters.

Conclusions

Nova will achieve the important ICF "ignition" milestone in the mid-1980s. The following papers describe the major subsystems which comprise this complex laser irradiation facility. The authors are indebted to LLNL Associate Directors J. L. Emmett and A. C. Haussmann for their support and encouragement in this important scientific and engineering endeavor.